Modelling of Gob Inertization with Nitrogen

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ABSTRACT

The paper deals with a modelling of nitrogen distribution throughout gob so that the effect of inertization could be measured. The model takes into account flow transient character, methane liberation and different locations for nitrogen injection. Computer modelling, reflecting mathematical models is done by a specially created computer programme NITRO_GOB, which allows dealing with different parameters of air leakage, of coal waste distribution as well as of gas picture in the gob before inertization. Effective evaluation of the most important parameters - injection place and nitrogen volume- on gob gas picture is illustrated under typical cross-section profiles of gas concentrations in gob depth and also under oxygen reduction in hazardous zones throughout gob surface. Thus the two aerodynamically linked parameters for object inertization control - place of injection and nitrogen amounts, can be studied. As a result of modeling, some changes in injection technology are suggested, leading to improvement of nitrogen distribution in SPONCOM hazard zones.

KEYWORDS

SPONCOM, Nitrogen inertization, Numerical Modelling, and Filtration Flow.

INTRODUCTION

SPONCOM fires in zones with self-initiated ventilation have always accompanied coal mining. Application of modern mechanised mining systems in long walls (both advancing and retreating) significantly increase extraction capacity of modern mines. Parallel to this a rapid growth in risk of coal self-heating in gob area is observed, affecting both components of this risk:

- fire hazard - concentrated in significant quantities of coal wastes, left after mining in coal seams with irregular hypsometry, which can't be followed by the mechanised machinery; increase in ventilation air and leakage through gob;
- fire damages - serious increase in total loss due to anti-fire isolation arising from great depreciation expenses and repair of expensive equipment and losses due to unproduced amounts.

In order to reduce the above mentioned increase in SPONCOM risk in sites where mechanised mining takes place, preventive and operational inertization with nitrogen is applied for SPONCOM control. In systems with long wall retreat mining, injection location and inertization regime are chosen empirically. Such approach leads to great expenses while at the same time low efficiency.

Very often both preventive and expeditious nitrogen injection in gob doesn't lead to target effect - either preventive or operational, of suppressing SPONCOM development. The main aim of the study is to reveal general facts and tendencies of relationship between mining technology (retreat long wall) parameters and SPONCOM risk distribution throughout gob area and on their basis - to draw out conclusions for optimal area of nitrogen injection application and its technical parameters.

PROBLEM FORMULATION

The empirical approach, which was applied in the creation and development of gob nitrogen injection technology can't provide adequate answers of the following (important for this technic efficiency) points:

⇒ what is the influence of natural changes in porous media on nitrogen distribution in gob;
⇒ how methane liberation and inertization affect oxygen content throughout gob;
⇒ how, if necessary, to change injection regime of preventive inertization in case of ignition evidence;
⇒ to what extent the increase of nitrogen amount influences inertization at given gob zones;
⇒ are there special hazard zones, where they are and how they change in the process of inertization;
⇒ is it possible for criteria for inertization optimization to be found.

Gasdynamical modeling of gob area can be a good basis for revealing the answers of some of the above stated problems, having in mind quazi-stationary mode of filtration flow. In solutions presented here gob area is arbitrarily fictionally into two calculation areas, as shown on Figure 1a:

- *"jet zone"* - nitrogen jet expansion zone $x \in (0 \div x_{end}); y \in (0 \div B)$ where the jet dissipates and looses its individuality. Solution in this zone is performed through the model and computer program NitroJet, presented in details in (Michaylov and Vlasseva, 1998). Aerodynamical parameters of this zone due to nitrogen injection are taken as follows: from computer programme GOB-VOID (Michaylov and Vlasseva, 1995) - pressure and velocity fields of air leakage; methane distribution - from GOB-METHANE (Michaylov and Vlasseva, 1996). Using the output of NitroJet, mutual boundary for jet and satellite flow is defined - location of the boundary, velocity profiles, nitrogen concentration, pressure. Significant reverse influence of satellite flow on nitrogen jet is not possible. That is why parameters and conditions, estimated at the end of jet zone are taken for boundary conditions for further nitrogen distribution in the rest greater gob part.
- *"nitrogen distribution zone"* - the part of gob outside the "jet zone" This zone is the one where nitrogen is distributed for the purpose of gob inertization and where it mixes with the satellite filtration flow. The process of distribution, values of nitrogen, oxygen and methane concentration throughout gob under varying injection location (Y_N) and amount (Q_N) are the object of this study. It is performed by computer program NITRO-GOB, which model, algorithm, realization and application is presented in detail in this paper.

MATHEMATICAL MODEL

Nitrogen flow distribution is considered two dimensionally. Interaction between NitroJet and NITRO-GOB takes place on their mutual boundary - the output of the first one becomes boundary condition for the second one thus forming some additional lines of the new calculation area (Figure 1a)

$x = B;\ y \in (0 \div y_j);\ y = y_j\ x \in (0 \div B)$.

The boundaries within which nitrogen distribution is studied, are as follows:

$\Rightarrow$ ①$_{in}$ - $0 \le x \le B;\ y = y_N$

This boundary location is evaluated by NitroJet and depends on place and velocity of injected nitrogen. Velocity profiles of W and nitrogen concentration alongside this boundary are taken from NItroJet computer program output. The mass balance takes into account not only injected nitrogen but satellite flow as well.

$\Rightarrow$ ②$_{in}$ $0 \le y \le y_N;\ x = B$

Air volumes are calculated in GOB-VOID;

$\Rightarrow$ ③$_{in}$ $B \le x \le x_{mid};\ y = 0$

This boundary presents part of porous boundary in air-leakage model GOB-VOID. Air volumes are taken from GOB-VOID. X_{mid} is a balance point, which marks the place where air leakage begins to outflow from gob and mix with main current;

$\Rightarrow$ ④$_{out}$ $x_{mid} \le x \le L_{f\,mid};\ y = 0$

Porous boundary on caving line where from gob the leaked-in air, liberated in gob methane and injected nitrogen outflow;

$\Rightarrow$ ⑤$_{mid}$ $0 \le y \le L_{g\,mid};\ x = x_{mid}$

Intermediate balance line where velocity profiles Wy change their direction. It divides conditionally the gob area into *left* and *right* part. In the model presented herewith it serves as control check place to verify whether the whole mass entered through boundaries ①$_{in}$, ②$_{in}$ и ③$_{in}$ have reached the balance line.

$\Rightarrow$ $y_N \le y \le L_g;\ x = 0$ - left, solid, nonpermiable boundary, alongside coal pillar of intake gallery;

$\Rightarrow$ $0 \le y \le L_g;\ x = L_f$ - right, solid, nonpermiable boundary, alongside coal pillar of outlet gallery;

$\Rightarrow$ $0 \le x \le L_f;\ y = y_{end}$ back of gob.

This boundary represents the place in gob depth where no air flow exist. The value Y_{END} is taken from GOB-VOID and in mathematical terms it is set that W=0;

Expressions describing the above mentioned boundaries are discussed in details elsewhere (Michaylov and Vlasseva, 1995, 1996). They are used in this study in the same way and that is why they are not discussed further.

Nitrogen and satellite flow distribution into gob in boundaries, defined above, obeys the following equations:

$$-\frac{\partial P}{\partial x} = (\alpha.\nu + \beta.|W_x|)\ \rho W_x \quad (1)$$

$$-\frac{\partial P}{\partial y} = (\alpha.\nu + \beta.|W_y|)\ \rho W_y \quad (2)$$

$$\frac{\partial(\rho W_x)}{\partial x} + \frac{\partial(\rho W_y)}{\partial y} = 0 \quad (3)$$

$$W_x \frac{\partial(\rho C_{N_2})}{\partial x} + W_y \frac{\partial(\rho C_{N_2})}{\partial y} - D_x \frac{\partial^2(\rho C_{N_2})}{\partial x^2} - D_y \frac{\partial^2(\rho C_{N_2})}{\partial y^2} = 0 \quad (4)$$

$$P = \frac{R\,T}{M}\rho \quad (5)$$

expressing energy conservation, Eq. (1,2), mass conservation of air-gas mixture Eq. (3) and injected nitrogen Eq. (4), equation of state Eq. (5) for mixture of air, methane and nitrogen.

The system 1-5 is transformed for obtaining the solution in the following way. ρW_x è ρW_y are expressed from Eq. (1) and Eq. (2) and are substituted into Eq. (3). These operations lead to Poison equation with variable coefficients:

$$\frac{\partial}{\partial x}\left(b\left(\frac{\partial P}{\partial x}\right)\right)+\frac{\partial}{\partial y}\left(c\left(\frac{\partial P}{\partial y}\right)\right)=0 \qquad (6)$$

where coefficients b(y); c(y) imply variable resistance coefficients throughout gob:

$$b(y)=\frac{1}{\alpha(x,y)\,\nu+\beta(x,y)\,|W_x|};\qquad c(y)=\frac{1}{\alpha(x,y)\,\nu+\beta(x,y)\,|W_y|}$$

Disregarding diffusion and assuming nonvariable density at a given part of gob the following expression is obtained from Eq. (4):

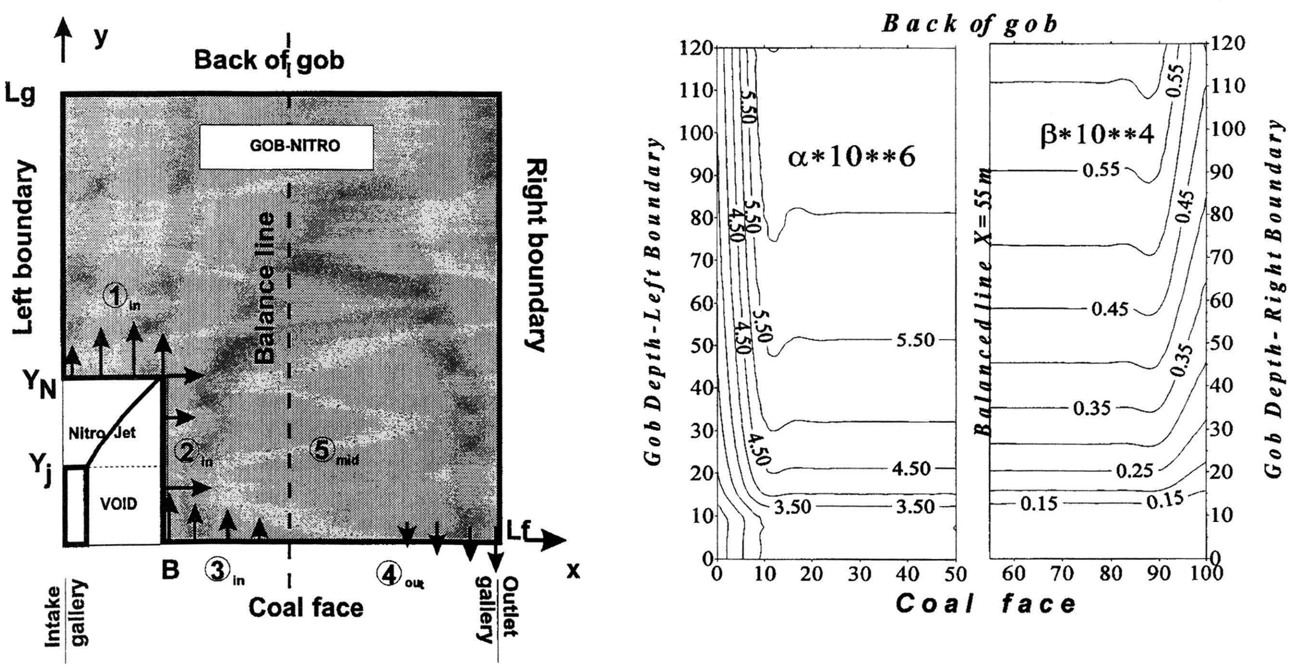
$$\frac{\partial(W_x C_{N_2})}{\partial x}+\frac{\partial(W_y C_{N_2})}{\partial y}=0 \qquad (4a)$$

The above expression is used in the modeling for controlling mass conservation in calculation area.

Gas constant and density for two-phase air-gas mixture (methane-air and nitrogen) is calculated under Dalton's law:

$$R_c^{\tilde{n}l}\cdot\frac{R_c^{N_2}R_c^{air}}{C_{N_2}R_c^{air}+\left(1-C_{N_2}\right)R_c^{N_2}} \qquad (7)$$

The mathematical model is solved in the following sequence. Initial values of pressure are evaluated by Eq. (6). They are used further in Eq. (1) and Eq. (2) to calculate velocity vectors. Gas concentrations are then obtained by Eq. (4a), using already defined velocity field. Then an iteration for new pressure throughout gob is done by equation of state Eq. (5) with more precise gas constant by Eq. (7).



a) *calculation area and boundaries* b) *resistance coefficients*

Figure 1. Gas dynamic model used in the study.

ALGORYTHM AND PROGRAMME GOB-NITRO

The mathematical model presented by Eq. (1-5) and supplied with boundary conditions is solved numerically. The area (gob) under consideration is transformed into set of points by implying regular net with steps on X → Δ x and on Y → Δy. Net functions are then defined, presenting both -media parameters (resistance coefficients α_{ij} и β_{ij}) and unknown functions (pressure - Pij, velocity - $W_x^{ij}; W_y^{ij}$, density ρij and concentration $C_{i,j}^{N_2}$). Net values for P, ρ and C are searched for (while at boundaries they are set) in net nodes. Velocity vector projections link separate points and are defined between points. Thus chess mesh is implied to solve the model numerically. The algorithm for solving 1, 2 and 5 is presented in details in (Michaylov, Vlasseva, 1995) and that is why it won't be discussed here. However, it is very important for the model of nitrogen distribution, presented here, because pressure and velocity field present initial values for satellite flow. Further in the process of calculations of nitrogen concentration, they change due to additional mass of injected nitrogen.

Equation 4 (mass conservation of nitrogen inflow) is solved by splitting on physical process (Belocherkovkii, 1984) - convection and diffusion:

$$W_x \frac{\partial C_{N_2}}{\partial x} + W_y \frac{\partial C_{N_2}}{\partial y} = 0 \tag{4b}$$

$$D_x \frac{\partial^2 C_{N_2}}{\partial x^2} + D_y \frac{\partial^2 C_{N_2}}{\partial y^2} = 0 \tag{4c}$$

From 4b written in finite differences assuming equal mesh steps Δ x and Δy for the two parts of gob, expressions for concentration in point i,j are obtained:

- for the left part
- $$C_{i,j} = \frac{Wx(i-1,j)C_{i-1,j} + Wy(i,j-1)C_{i,j-1}}{Wx(i-1,j) + Wy(i,j-1)} \tag{8a}$$

- for the right part

$$C_{i,j} = \frac{Wx(i-1,j)C_{i-1,j} + ABS(Wy(i,j))C_{i,j+1}}{Wx(i-1,j) + ABS(Wy(i,j))} \tag{8b}$$

Five point pattern (Samarskii, 1982) is applied to (4c) which leads to the following expression for concentration in point with co-ordinates i,j:

$$C_{i,j} = \frac{1}{4}\left(C_{i-1,j} + C_{i+1,j} - C_{i,j-1} + C_{i,j+1}\right) \tag{8}$$

This expression is a basis for iteration procedure which ties down all points of calculation mesh - POISON (presented in full in Michaylov, 1994; Michaylov, 1995). At this study the only difference is the unknown function Ci,j.

Nitrogen concentration distribution follows the velocity field. Nitrogen injection inputs additional mass into gob. That is why before merging the two fields (velocity and concentration) velocity field should be precalculated, i.e. gob aerodynamics (procedure GOB-VOID) is carried put. Its output are the new velocity field Wi,j with vectors projections Wx and Wy; pressure Pi,j and density ρi,j. Iteration procedure converges on pressure values, which are in range 10^5 Pa, while velocities are in range 10^{-3} m/s. This lead to errors, which expand in the process of calculations and as a result mass balance in special cross-sections is infringed. That is why the following controls for minimizing the errors are implied:

- for the left part (0≤x≤aLf; 0≤y≤Lg) by columns (x=const)

$$\sum_i Wx^{in} + Wy(i+1,0) = \sum_{i+1} Wx^{out}$$

- for the right part (aLf≤x≤Lf; Lg≥y≥0)

by rows (y=const) from back towards porous boundary

$$x^{mid} + \sum_j Wy^{in} = \sum_{j-1} Wy^{out}$$

by columns (x=const) $\sum_i Wx^{in} - \sum_{i+1} Wx^{out} = Wy(i+1,0)$

Similar controls are fulfilled for nitrogen volumes:

- for the left part

$$\sum_i Wx^{in} C^{in}_{N_2} + Wy(i+1, Y_N) C^{Y_N}_{N_2} = \sum_{i+1} Wx^{out} C^{out}_{N_2}$$

- through boundaries ①$_{in}$ и ⑤$_{mid}$

$$\sum_{1_{in}} C^{in}_{N_2} Wy(i, y_N) = \sum_{5_{mid}} C_{N_2} Wy$$

- for the right part

$$C^{mid}_{N_2} Wx^{mid} + \sum_j C^{in}_{N_2} Wy^{in} = \sum_{j-1} C^{out}_{N_2} Wy^{out}$$

$$\sum_i C^{in}_{N_2} Wx^{in} - \sum_{i+1} C^{out}_{N_2} Wx^{out} = C_{N_2}(i+1,0)\ Wy(i+1,0)$$

$$\sum_{1_{in}} C^{in}_{N_2} Wy(i, y_N) = \sum_{4_{out}} C_{N_2} Wy$$

Following the above procedure values for technical nitrogen concentration for every point of calculation area including right part of porous boundary are obtained. These values are considered as input data for GOB-METHANE and final outcome of modelling is achieved: recalculated concentrations of methane, nitrogen (technical and airborne) and oxygen (from air and from technical nitrogen).

Computer programme GOB-NITRO, reflecting the above presented algorithm is created. It has modulus structure. Each modulus present separate computer procedure and completed problem. The names of the modules, their purpose, information links between them are shown in Table 1. Interaction of GOB-NITRO with GOB-VOID and GOB-METHANE is presented on Figure 2.

NUMERICAL EXPERIMENTS

Numerical experiments were carried out for coal face with length Lf=100m. Main air current for ventilation of the face had initial methane concentration 0.25%vol. Nitrogen was injected along the edge of the abandoned intake roadway. Technical nitrogen purity (oxygen content) in all experiments was assumed 2%vol. The following variations

Table 1. Modules and data files used in the gob inertization modelling.

Name	Purpose	Input	Output
DATA_INPUT	Inputs values for technological and geometrical parameters of gob and inertization regime. Inputs basic velocity and pressure fields from GOB-VOID	data file GOB-VOID	transfers information to other modules
GOB_RES	Calculates viscous and inertial resistance coefficients αij and βij (Michaylov and Vlasseva, 1995).	DATA-INPUT	transfers information to other modules
POISON_A	On initial velocity and pressure fields, taken from GOB-VOID additional mass is balanced through gob. New values for Pij, Wx(i,j) and Wy(i,j).	DATA-INPUT GOB-RES	GOB-C
GOB_C	Via consecutive passes through mesh points from left, by balanced line to right part of gob technical nitrogen concentration is evaluated	POISON-A	POISON-C
POISON_C	Sequence between pressure, velocity and concentration fields.	GOB_C	Final results

in the main technological parameters, important for the process of injection were considered:

- place of injection - depth in gob from Y_N = 15m to Y_N=45m behind the caving line;
- volume of injected nitrogen - from Q_N=600 m³/h to Q_N=3000 m³/h.

Table 2. Nitrogen injected and gob leakage used in the example.

Volumetric ratio	Injected nitrogen, m³/h				
	600	1200	1800	2400	3000
Q^N/q^L	0,187	0,373	0,561	0,747	0,934
q^m/q^L	0,0673	0,0673	0,0673	0,0673	0,0673
q^m/Q^N	0,36	0,180	0,120	0,090	0,072
$(q^m+Q^N)/q^L$	0,254	0,441	0,627	0,814	1,000
Q^N/Q^f	0,208	0,0416	0,0625	0,0833	0,104

Some characteristics for the experiment, quantitative ratio between the amount of injected nitrogen Q_N, air leakage into gob q^L and rate of methane liberation in gob q^m, are given in Table 2. Some of the results are shown on Figure 3-Figure 6. Gob contours for all the graphs at these figures correspond to the boundaries, explained in the model and shown on Figure 1.

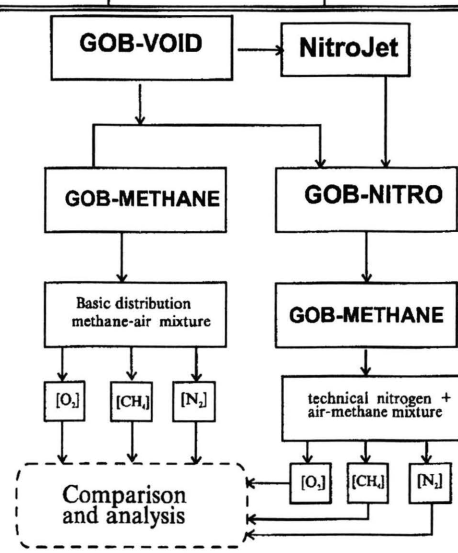


Figure 2. Interaction between programes.

DISCUSSION

Porous media formation into gob is a natural, non-controllable process which affects significantly the nitrogen distribution in the job. Coal face operational period should be considered into two specific time stages:

- from the initial gallery to first fracture of the main roof;
- after the first fracture of the main roof.

In a well developed gob area, observed in the second stage, viscous and inertial coefficients change as shown on Figure 1b. In the vicinity of porous, left and right boundary zones with less aerodynamic resistance are formed compared with the central part of gob.

At the first stage (due to first fracture of the main roof) such uncompacted boundary is the back one, which is the initial gallery of the wall face. Thus, alongside gob contour, zones with little resistance are formed, where compactness (decrease of porosity) takes place twice as slowly than in central parts of gob. Greater permeability in contour vicinity leads to flowing of significant amounts of air leakage and injected nitrogen through it. That is why well performed artificial compactness of this contour is one of the most essential technical measures for effective nitrogen distribution through the rest of gob area, besides channel-like contour, naturally formed in the first 3-4 months of coal face operation. Parallel to this measure to break aerodynamical link with initial gallery after the fracture of the main roof; it is necessary to perform effective construction chamber compactness, for instance by slurring.

Our previous experiments performed with variable methane liberation characteristics show that when methane liberation increases, dangerous methane concentration zones swing against filtration flow (anti-clockwise). Specific detail, granted by high resistance of the central part, is that at 5-10 meters to the right of the balance line, zones exist where methane concentration changes slowly.

Concentration of oxygen and methane isolines alongside left and right boundaries (Figure 3a,b-6a,b) is caused by resistance changes (Figure 1b) of porous media around contours.

Increase in the amount of injected nitrogen leads to swing along flow direction of low oxygen concentrations (Figure 3b-Figure 6b). Around left and right boundaries two trapezoid twist zones with low oxygen concentrations are formed.

Increase in injection depth reduces difference in oxygen concentrations in input and outlet galleries (Figure3b-Figure 6b), though around input gallery concentration is more hazardous for SPONCOM than around the outlet one. On the basis of velocity and concentration fields, obtained in numerous experiments, a good antifire measure can be the construction of foam plastic stopping alongside gob contour but only in the first stage (due to first fracture of the main roof). In more developed stages of long wall operation such stopping does not effect significantly gas distribution in the vicinity of outlet gallery coal pillar. At the same time they prolong leakage way thus helping greater amounts of heat accumulation in outlet gallery pillar.

Nitrogen effect on oxygen concentrations can be clearly valued by the graph on Figure 7. Curves present relative decrease in oxygen concentrations in gob before and after injection. Difference of 1 characterize inertization effectiveness. Dimensionless concentration $[\overline{O_2}]$ = 0.5, shown on charts with thicker line indicate two times reduction of oxygen due to injection.

On increase of the amount of injected nitrogen low oxygen zones draw upward to the injection place. Another conclusion can be drawn: Nitrogen amounts of Q_N=2400 m^3/h and higher (charts with index "c" on Figures 3-6 and 7d) when injected show a tendency for outflow of nitrogen through first half of porous boundary. Such tendency is observed even when Q_N=1800 m^3/h and injection place is 15 m behind the caved line, while, when Q_N=2400 m^3/h, the place is 25 m and more. Increased amount of injected nitrogen makes the zones of high (over 5%) and dangerous (5%-15%) methane concentrations narrower (Figure 3a - Figure 6a). This shrink takes place mainly via shift of Low Explosion Limit (5%) backward and towards right boundary. Shrink is most significant in gob depth from 60 to 80 m. Ratio between injected nitrogen and liberated methane is as much as up to 14 times (Table 2).

In order to analyze again contour effects alongside left and right boundary and nitrogen distribution throughout gob area, cross sections of oxygen concentration in gob depth at 5 m from left and right boundaries and at balanced line are presented on Figure 7. Charts on these graphs have the following meaning:

● x=5m - oxygen profile in gob depth 5 m from coal pillar of input gallery;

O x=95m - oxygen profile in gob depth 5 m from coal pillar of outlet gallery;

□ x=55 m - oxygen profile in gob depth at balance line, 55 m from coal pillar of input gallery;

On the four graphs oxygen concentration alongside balance line (x=55 m) is higher than close to boundaries (x=5 and x=95 m). This tendency is the same in all injected amounts from Q_N=600 m^3/h (Figure .8a) to Q_N=2400 m^3/h (Figure 8d) and at a three-fold increase of injection depth - from Y_N =15m (Figure 8a) to Y_N =45m (Figure 8d). Without any doubts the conclusion can be drawn that such tendency is due to aerodynamical resistance of porous media (Figure 1b). This tendency in oxygen concentration cannot be changed only by changing injected amounts but by changing injected technology via type of injection source. With increase of injection depth slope of oxygen profile at balance line (x=55 m) becomes sheerer (Y_N =35m and Q_N=1800 m^3/h and more).

Around balance line flow direction is parallel to face (Wy=0). This means that in that vicinity intensification of inert gas amounts and cooling due to convection without change in injection regime cannot be achieved. A dangerous oxygen zone around balance line exists. In numerical experiments presented here (Table 2) oxygen concentration on line remains higher that 15% at 15 m to 55 m behind the caving line and 10% - at 45 m to 70 m behind the caving line.

Velocities are smaller at equal distances behind the face at balance line compared with the ones near the contour, which means that heat transfer due to convection is worse at the central gob part.

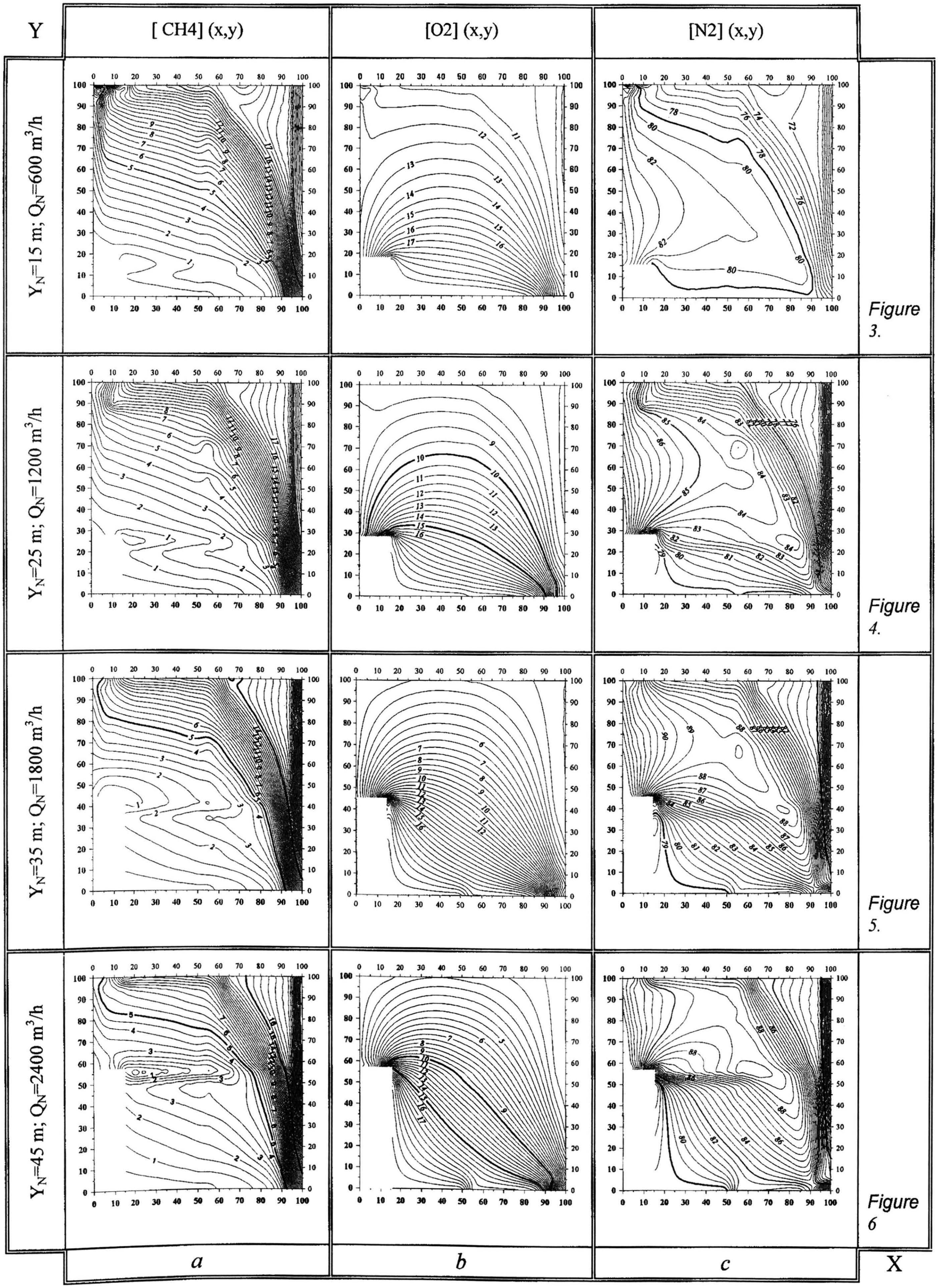


Figure 3.

Figure 4.

Figure 5.

Figure 6

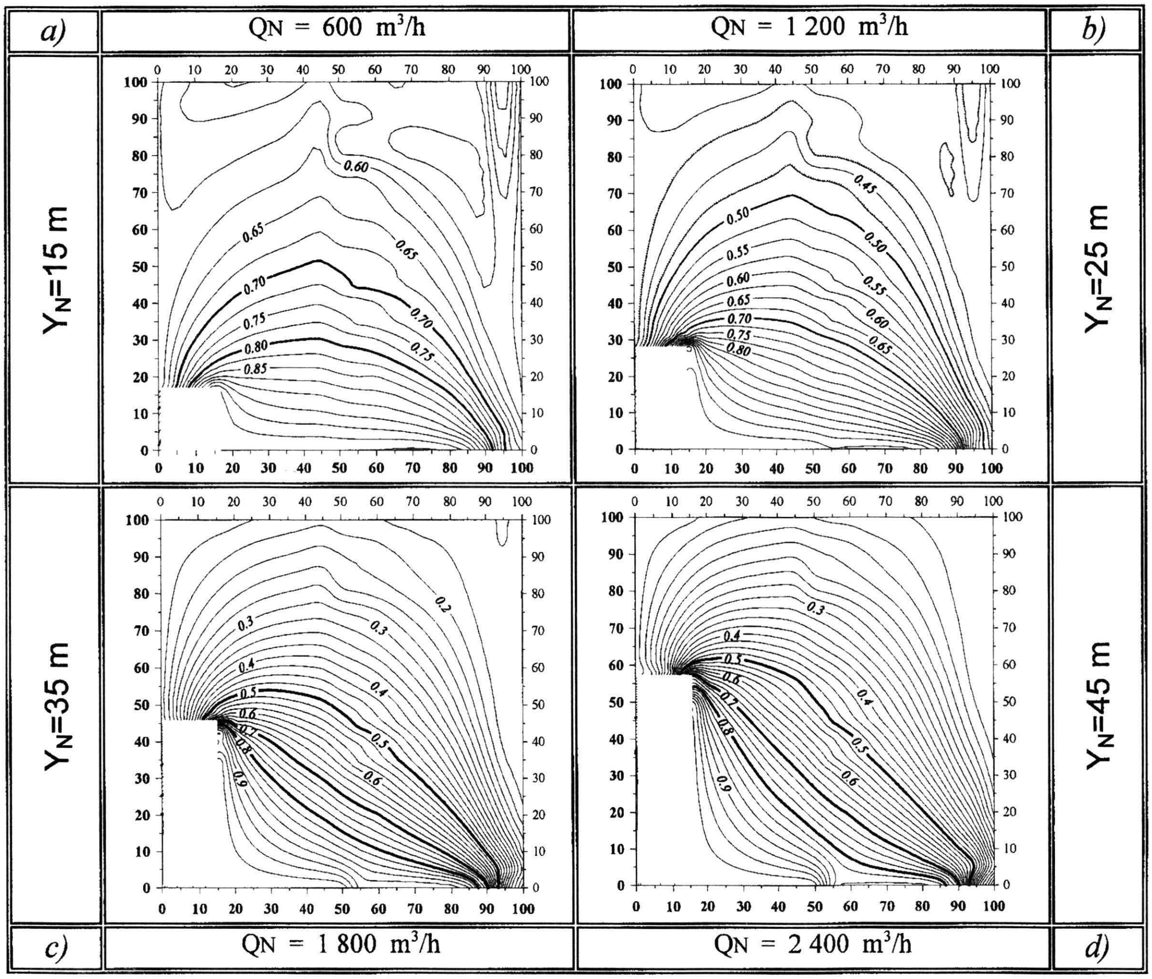


Figure 7. Dimensionless oxygen concentration $\left[\overline{O}_2\right]$ after inertization.

Behind the injection place (Y_N on Figure 1a) in all numerical experiments nitrogen concentration shadow is observed, where oxygen concentration does not change significantly. The shadow has a curved triangle shape with basis at the axis x (Figure 1a) parallel to cave line y=0. The slope of the curved triangle side depends on amount and place of injection (Figure 3b - Figure 6b). Increase in injected amounts QN leads to clockwise rotation thus shorting the nonsensitive to inertization zone. This leads to outflow of nitrogen through the first half of porous boundary (before the balance line) which subsequently reflects into less efficiency of inertization process.

CONCLUSION

Nitrogen inertization of gob to prevent and suppress SPONCOM is not a universal measure as the 15 year Bulgarian experience in its application shows. Theoretical study (Project 123, 1998) gives explanation why, even when treated with nitrogen, some SPONCOM in longwall faces have developed. Studying gas and temperature measurements conducted during the real fire, which took place in Nov. 1998 at "Babino" mine during dismantling of mechanised complex at end gallery of panel 421-5m, gave both qualitative and quantitative verification of numerical modeling results. Location and size of oxygen dangerous zones happen to be the same which substantiates suggested measures in additional to inertization, in order to compress and cool the porous media more effectively.

Inertization efficiency requires changes in technique and regime of the process in regard to place and way of injection accompanied with other technologies for compensation of dangerous zones nonsensitive to nitrogen injection. Some possible solutions are presented in (Michaylov and Vlasseva, 1998). Having performed more than 70 numerical experiments, the authors have ground to state that the model and computer program GOB-NITRO can be used to solve forecast, design and operation problems, connected with inertization process. It can be used also for estimation of new technical measures, solutions and technologies for inertization improvement.

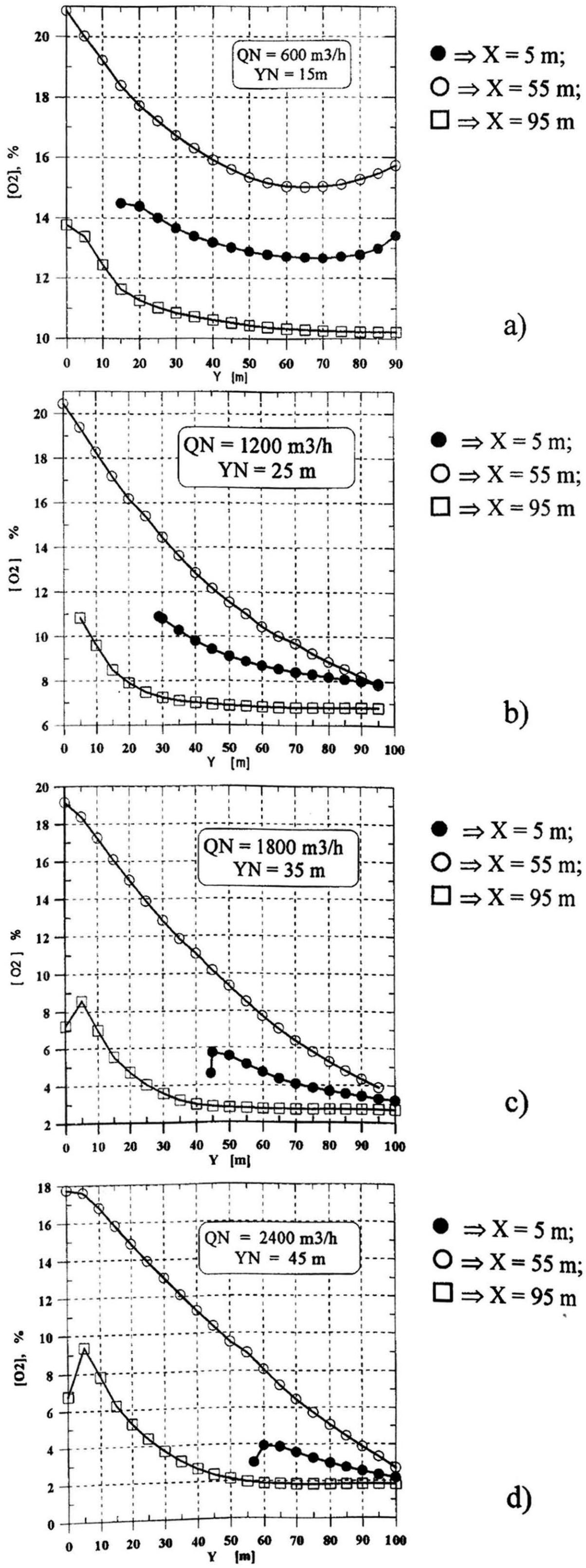


Figure 8. Cross-section profiles of oxygen concentration.

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